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14. ABSTRACT
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15. SUBJECT TERMS
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# RPPR Final Report

## as of 06-Dec-2022

Agency Code: 21XD

Proposal Number: 68479NSRIP

Agreement Number: W911NF-16-1-0224

### INVESTIGATOR(S):

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DUNS Number: 047120084

EIN: 946036494

**Report Date:** 31-Aug-2019

Date Received: 12-Aug-2022

**Final Report** for Period Beginning 01-Jun-2016 and Ending 31-May-2019

**Title:** Millimeter Wave Human Tracking and Activity Monitoring

**Begin Performance Period:** 01-Jun-2016

**End Performance Period:** 31-May-2019

**Report Term:** 0-Other

Submitted By: Prasant Mohapatra

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**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

### STEM Degrees:

### STEM Participants:

#### Major Goals: 1. Objectives

Millimeter wave (mmWave) signal reflected from the human body can be exploited for human mobility tracking and accurate activity monitoring. It can enable indoor scanning radars with many potential applications such as ubiquitous, non-invasive vital sign monitoring, target tracking, and gait analysis. The main objective of this work is to develop a state-of-the-art mmWave networking and sensing testbed. The infrastructure will be used to design and evaluate human mobility tracking and motion profiling with accurate channel information and analysis of the reflected signal.

#### 2. Research Infrastructure

The requested equipment and its usage can be summarized as follows.

(i) Software radio platforms and 60 GHz RF front-end modules: They will allow us to build mmWave sensing transmitter and receivers wideband signal transmission and detailed channel information of the reflected signal, along with the development of PHY/MAC protocols for mmWave networking and sensing.

(ii) Spectrum analyzer 60 GHz extension modules and oscilloscope: They will provide a fine-grained wireless signal profile in frequency and time domains necessary for accurate motion detection such as vital sign monitoring, activity and gesture recognition, and gait analysis.

(iii) Programmable rotator and slider: It will facilitate the design of scanning radar where mmWave beam direction can be changed by mounting the horn antennas on the rotator/slider. With horn antennas of different beamwidths, it will allow us to study human tracking at different spatial resolutions.

#### 3. Research Thrusts and Challenges

In our proposed research, we will design and implement indoor mmWave radar by reusing 60 GHz communication infrastructure. This requires us to solve the following challenges:

(i) The mmWave signal is reflected by many types of objects in an indoor environment. Hence, it is necessary to distinguish signals reflected off a human body from other reflections. We will develop novel methodologies to distinguish body reflections from ambient reflections.

(ii) The signal reflected from the human body is highly dependent on the angle of incidence of the signal. It is essential to develop analytical models supported by experimental evaluation to fundamentally understand the impact of factors such as incident angle and the human body's permittivity on the reflected signal.

(iii) The scanning radar should be able to deal with human mobility. Adaptive beamwidth dilation and indoor reflection profiling can be utilized for accurate and efficient tracking of a mobile target.

## RPPR Final Report as of 06-Dec-2022

(iv) Indoor objects can block the mmWave signal from impinging the human body. We will explore solutions like scanner infrastructure mobility, multiple distributed scanners, and beamwidth adaptation for human tracking in the presence of a signal blockage.

### **Accomplishments:** 4. Infrastructure Development and Research Accomplishments

Equipment:

WARP v3: <https://www.mangocomm.com/products/kits/warp-v3-kit/>

VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghzdevelopment-system-low-phase-noise-pem009-kit-p.aspx>

Motorized rotators: <https://cinetics.com/axis360-pro/>

Project: 60 GHz millimeter-wave networks have emerged as a potential candidate for designing the next generation of multi-gigabit WLANs. Since the 60 GHz links suffer from frequent outages due to blockages caused by human mobility, deploying 60 GHz WLANs that can provide robust coverage in presence of blockages is a challenging problem. In this paper, we study blockage-aware coverage and deployment of 60 GHz WLANs. We first show that the reflection profile of an indoor environment can be sensed using a few measurements. A novel coverage metric (angular spread coverage) which captures the number of available paths and their spatial diversity is proposed. Additionally, it is shown that using relays can extend the coverage of the AP at a lower cost and provide added spatial diversity in the available paths. We propose a heuristic algorithm that determines the AP and relay locations while maximizing the angular spread coverage metric for the clients. Our testbed-based evaluation shows that for five different rooms, our proposed deployment can guarantee an average connectivity of 91.7%, 83.9%, and 74.1% of client locations in the presence of 1, 3 and 5 concurrent human blockages respectively, substantially increasing the robustness of 60 GHz links against blockages.

Publication: Yang, Z., Pathak, P. H., Pan, J., Sha, M., & Mohapatra, P. (2018, October). Sense and deploy: Blockage-aware deployment of reliable 60 GHz mmWave WLANs. In 2018 IEEE 15th International Conference on Mobile Ad Hoc and Sensor Systems (MASS) (pp. 397-405). IEEE.

Equipment:

VubIQ PEM-004 board to generate the baseband sine wave signals and use VubIQ PEM-009 60

GHz RF front-end development kit: <https://www.pasternack.com/60-ghz-development-system-low-phasenoise-pem009-kit-p.aspx>

<https://www.pasternack.com/60-ghz-baseboard-i-q-module-pem004-p.aspx>

Keysight DSOS254A oscilloscope: <https://www.keysight.com/au/en/product/DSOS254A/highdefinition-oscilloscope-2-5-ghz-4-analog-channels.html>

Project: With the development of novel sensing techniques, continuous monitoring, data-driven inferences, precision irrigation control, and intelligent Internet-of-Things (IoT) systems, agriculture sector is witnessing a revolution. Specialized devices based on infrared and laser are developed to assist farmers in assessing the produce quality, especially its sugar content. However, such devices are expensive and not readily available to consumers. In this paper, we investigate the feasibility of using 60 GHz millimeter-wave (mmWave) signal as a ubiquitous and non-invasive way to estimate the Soluble Sugar Content (SSC) in fruits. With the rapid development in the mmWave technology, 60 GHz WiFi is likely to become pervasive in future mobile devices. Our study shows that when 60 GHz WiFi signals reflect from a fruit, the reflection can be used to infer the fruit's sugar content. We identify the underlying reasons of variations in reflection signals with varying SSC and study the impact of size, shape and density of fruits on reflections. We then develop statistical features based on received signal strength and amplitude, and use them to design regression-based estimation models. With an extensive evaluation with 300 fruit samples, we find that our proposed technique can estimate SSC in three different type of fruits with an average correlation coefficient of 85%. Our prediction errors are within the range of user's taste perception.

Publication: Yang, Z., Pathak, P. H., Sha, M., Zhu, T., Gan, J., Hu, P., & Mohapatra, P. (2019, April).

On the feasibility of estimating soluble sugar content using millimeter-wave. In Proceedings of the International Conference on Internet of Things Design and Implementation (pp. 13-24).

Equipment:

VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghzdevelopment-system-low-phase-noise-pem009-kit-p.aspx>

Project: In recent years, millimeter-wave (mmWave) is becoming a significant component of the next generation wireless communication due to its up to 7 Gbps transmission rate. In addition to the communication benefits, the unique sensing feature of mmWave attracts more attention. Nowadays, the services of human detection and identification are needed in numerous application scenarios, such as smart home and smart industry. The RF-based sensing techniques, especially WiFi-based, are widely

## RPPR Final Report as of 06-Dec-2022

utilized in human detection and identification. However, these work either require humans to carry devices or cannot detect and identify multiple people simultaneously. In this paper, we propose mmSense, a device-free multi-person detection and identification framework, which exploits the unique mmWave sensing features. First, we utilize the properties of directionality, impenetrability, and reflection of 60 GHz signal for objects to fingerprint the environments. Based on the generated environment fingerprints with and without human presence, mmSense can detect and localize the presence of multiple people simultaneously via the LSTM-based classification model. Moreover, we propose a novel approach to use humans' outline profile and vital signs to identify multiple people by using 60 GHz reflected signals of the human body. We conduct extensive experiments to demonstrate the low-cost and effectiveness of our approach.

Publication: Gu, T., Fang, Z., Yang, Z., Hu, P., & Mohapatra, P. (2019, October). MmSense: Multiperson detection and identification via mmWave sensing. In Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems (pp. 45-50).

Equipment:

VubiQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghztest-development-system-pem003-kit-p.aspx>

Project: Continuous monitoring of human's breathing and heart rates is useful in maintaining better health and early detection of many health issues. Designing a technique that can enable contactless and ubiquitous vital sign monitoring is a challenging research problem. This paper presents mmVital, a system that uses 60 GHz millimeter wave (mmWave) signals for vital sign monitoring. We show that the mmWave signals can be directed to human's body and the RSS of the reflections can be analyzed for accurate estimation of breathing and heart rates. We show how the directional beams of mmWave can be used to monitor multiple humans in an indoor space concurrently. mmVital relies on a novel human finding procedure where a human can be located within a room by reflection loss based object/human classification. We evaluate mmVital using a 60 GHz testbed in home and office environment and show that it provides the mean estimation error of 0.43 Bpm (breathing rate) and 2.15 bpm (heart rate). Also, it can locate the human subject with 98.4% accuracy within 100 ms of dwell time on reflection. We also demonstrate that mmVital is effective in monitoring multiple people in parallel and even behind the wall.

Publication: Yang, Z., Pathak, P. H., Zeng, Y., Liran, X., & Mohapatra, P. (2016, July). Monitoring vital signs using millimeter wave. In Proceedings of the 17th ACM international symposium on mobile ad hoc networking and computing (pp. 211-220).

**Training Opportunities:** Two graduate students and a postdoctoral associate were trained on the equipment.

**Results Dissemination:** 5. Publications Summary

(i) Tianbo Gu, Zheng Fang, Zhicheng Yang, Pengfei Hu, and Prasant Mohapatra. 2019. MmSense: Multi-Person Detection and Identification via mmWave Sensing. In Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems (mmNets'19). Association for Computing Machinery, New York, NY, USA, 45–50.

(ii) T. Gu, Z. Yang, D. Basu and P. Mohapatra, "BeamSniff: Enabling Seamless Communication under Mobility and Blockage in 60 GHz Networks," in 2019 IFIP Networking Conference (IFIP Networking), Warsaw, Poland, 2019 pp. 1-9.

(iii) Z. Yang, P. H. Pathak, J. Pan, M. Sha and P. Mohapatra, "Sense and Deploy: Blockage-Aware Deployment of Reliable 60 GHz mmWave WLANs," 2018 IEEE 15th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), 2018, pp. 397-405.

(iv) Zhicheng Yang, Parth H. Pathak, Yunze Zeng, Xixi Liran, and Prasant Mohapatra. 2017. Vital Sign and Sleep Monitoring Using Millimeter Wave. ACM Trans. Sen. Netw. 13, 2, Article 14 (May 2017), 32 pages.

(v) Z. Yang, P. H. Pathak, Y. Zeng and P. Mohapatra, "Sensor-Assisted Codebook-Based Beamforming for Mobility Management in 60 GHz WLANs," 2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems, 2015, pp. 333-341.

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

**RPPR Final Report**  
as of 06-Dec-2022

**PARTICIPANTS:**

**Participant Type:** PD/PI

**Participant:** Prasant Mohapatra

**Person Months Worked:** 1.00

Project Contribution:

National Academy Member: N

**Funding Support:**

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)

**Participant:** Parth Pathak

**Person Months Worked:** 2.00

Project Contribution:

National Academy Member: N

**Funding Support:**

**Participant Type:** Graduate Student (research assistant)

**Participant:** Zhicheng Yang

**Person Months Worked:** 3.00

Project Contribution:

National Academy Member: N

**Funding Support:**

**Partners**

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I certify that the information in the report is complete and accurate:

Signature: Prasant Mohapatra

Signature Date: 8/12/22 7:37PM

# **Millimeter Wave Human Tracking and Activity Monitoring**

Prasant Mohapatra, University of California, Davis

## **Final Report for DURIP Grant W911NF1610224 / 68479-NS-RIP**

### **1. Objectives**

Millimeter wave (mmWave) signal reflected from the human body can be exploited for human mobility tracking and accurate activity monitoring. It can enable indoor scanning radars with many potential applications such as ubiquitous, non-invasive vital sign monitoring, target tracking, and gait analysis. The main objective of this work is to develop a state-of-the-art mmWave networking and sensing testbed. The infrastructure will be used to design and evaluate human mobility tracking and motion profiling with accurate channel information and analysis of the reflected signal.

### **2. Research Infrastructure**

The requested equipment and its usage can be summarized as follows.

(i) Software radio platforms and 60 GHz RF front-end modules: They will allow us to build mmWave sensing transmitter and receivers wideband signal transmission and detailed channel information of the reflected signal, along with the development of PHY/MAC protocols for mmWave networking and sensing.

(ii) Spectrum analyzer 60 GHz extension modules and oscilloscope: They will provide a fine-grained wireless signal profile in frequency and time domains necessary for accurate motion detection such as vital sign monitoring, activity and gesture recognition, and gait analysis.

(iii) Programmable rotator and slider: It will facilitate the design of scanning radar where mmWave beam direction can be changed by mounting the horn antennas on the rotator/slider. With horn antennas of different beamwidths, it will allow us to study human tracking at different spatial resolutions.

### **3. Research Thrusts and Challenges**

In our proposed research, we will design and implement indoor mmWave radar by reusing 60 GHz communication infrastructure. This requires us to solve the following challenges:

(i) The mmWave signal is reflected by many types of objects in an indoor environment. Hence, it is necessary to distinguish signals reflected off a human body from other reflections. We will develop novel methodologies to distinguish body reflections from ambient reflections.

(ii) The signal reflected from the human body is highly dependent on the angle of incidence of the signal. It is essential to develop analytical models supported by experimental evaluation to fundamentally understand the impact of factors such as incident angle and the human body's permittivity on the reflected signal.

(iii) The scanning radar should be able to deal with human mobility. Adaptive beamwidth dilation and indoor reflection profiling can be utilized for accurate and efficient tracking of a mobile target.

(iv) Indoor objects can block the mmWave signal from impinging the human body. We will explore solutions like scanner infrastructure mobility, multiple distributed scanners, and beamwidth adaptation for human tracking in the presence of a signal blockage.

## 4. Infrastructure Development and Research Accomplishments

### Equipment:

WARP v3: <https://www.mangocomm.com/products/kits/warp-v3-kit/>

VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghz-development-system-low-phase-noise-pem009-kit-p.aspx>

Motorized rotators: <https://cinetics.com/axis360-pro/>

**Project:** 60 GHz millimeter-wave networks have emerged as a potential candidate for designing the next generation of multi-gigabit WLANs. Since the 60 GHz links suffer from frequent outages due to blockages caused by human mobility, deploying 60 GHz WLANs that can provide robust coverage in presence of blockages is a challenging problem. In this paper, we study blockage-aware coverage and deployment of 60 GHz WLANs. We first show that the reflection profile of an indoor environment can be sensed using a few measurements. A novel coverage metric (angular spread coverage) which captures the number of available paths and their spatial diversity is proposed. Additionally, it is shown that using relays can extend the coverage of the AP at a lower cost and provide added spatial diversity in the available paths. We propose a heuristic algorithm that determines the AP and relay locations while maximizing the angular spread coverage metric for the clients. Our testbed-based evaluation shows that for five different rooms, our proposed deployment can guarantee an average connectivity of 91.7%, 83.9%, and 74.1% of client locations in the presence of 1, 3 and 5 concurrent human blockages respectively, substantially increasing the robustness of 60 GHz links against blockages.

**Publication:** Yang, Z., Pathak, P. H., Pan, J., Sha, M., & Mohapatra, P. (2018, October). Sense and deploy: Blockage-aware deployment of reliable 60 GHz mmWave WLANs. In *2018 IEEE 15th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)* (pp. 397-405). IEEE.

### Equipment:

VubIQ PEM-004 board to generate the baseband sine wave signals and use VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghz-development-system-low-phase-noise-pem009-kit-p.aspx>

<https://www.pasternack.com/60-ghz-baseboard-i-q-module-pem004-p.aspx>

Keysight DSOS254A oscilloscope: <https://www.keysight.com/au/en/product/DSOS254A/high-definition-oscilloscope-2-5-ghz-4-analog-channels.html>

**Project:** With the development of novel sensing techniques, continuous monitoring, data-driven inferences, precision irrigation control, and intelligent Internet-of-Things (IoT) systems, agriculture sector is witnessing a revolution. Specialized devices based on infrared and laser are developed to assist farmers in assessing the produce quality, especially its sugar content. However, such devices are expensive and not readily available to consumers. In this paper, we investigate the feasibility of using 60 GHz millimeter-wave (mmWave) signal as a ubiquitous and non-invasive way to estimate the Soluble Sugar Content (SSC) in fruits. With the rapid development in the mmWave technology, 60 GHz WiFi is likely to become pervasive in future mobile devices. Our study shows that when 60 GHz WiFi signals reflect

from a fruit, the reflection can be used to infer the fruit's sugar content. We identify the underlying reasons of variations in reflection signals with varying SSC and study the impact of size, shape and density of fruits on reflections. We then develop statistical features based on received signal strength and amplitude, and use them to design regression-based estimation models. With an extensive evaluation with 300 fruit samples, we find that our proposed technique can estimate SSC in three different type of fruits with an average correlation coefficient of 85%. Our prediction errors are within the range of user's taste perception.

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#### **Equipment:**

VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghz-development-system-low-phase-noise-pem009-kit-p.aspx>

**Project:** In recent years, millimeter-wave (mmWave) is becoming a significant component of the next-generation wireless communication due to its up to 7 Gbps transmission rate. In addition to the communication benefits, the unique sensing feature of mmWave attracts more attention. Nowadays, the services of human detection and identification are needed in numerous application scenarios, such as smart home and smart industry. The RF-based sensing techniques, especially WiFi-based, are widely utilized in human detection and identification. However, these work either require humans to carry devices or cannot detect and identify multiple people simultaneously. In this paper, we propose mmSense, a device-free multi-person detection and identification framework, which exploits the unique mmWave sensing features. First, we utilize the properties of directionality, impenetrability, and reflection of 60 GHz signal for objects to fingerprint the environments. Based on the generated environment fingerprints with and without human presence, mmSense can detect and localize the presence of multiple people simultaneously via the LSTM-based classification model. Moreover, we propose a novel approach to use humans' outline profile and vital signs to identify multiple people by using 60 GHz reflected signals of the human body. We conduct extensive experiments to demonstrate the low-cost and effectiveness of our approach.

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#### **Equipment:**

VubIQ PEM-009 60 GHz RF front-end development kit: <https://www.pasternack.com/60-ghz-test-development-system-pem003-kit-p.aspx>

**Project:** Continuous monitoring of human's breathing and heart rates is useful in maintaining better health and early detection of many health issues. Designing a technique that can enable contactless and ubiquitous vital sign monitoring is a challenging research problem. This paper presents mmVital, a system that uses 60 GHz millimeter wave (mmWave) signals for vital sign monitoring. We show that the mmWave signals can be directed to human's body and the RSS of the reflections can be analyzed for accurate estimation of breathing and heart rates. We show how the directional beams of mmWave can be

used to monitor multiple humans in an indoor space concurrently. mmVital relies on a novel human finding procedure where a human can be located within a room by reflection loss based object/human classification. We evaluate mmVital using a 60 GHz testbed in home and office environment and show that it provides the mean estimation error of 0.43 Bpm (breathing rate) and 2.15 bpm (heart rate). Also, it can locate the human subject with 98.4% accuracy within 100 ms of dwell time on reflection. We also demonstrate that mmVital is effective in monitoring multiple people in parallel and even behind the wall.

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## 5. Publications Summary

- (i) Tianbo Gu, Zheng Fang, Zhicheng Yang, Pengfei Hu, and Prasant Mohapatra. 2019. MmSense: Multi-Person Detection and Identification via mmWave Sensing. In *Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems (mmNets'19)*. Association for Computing Machinery, New York, NY, USA, 45–50.
- (ii) T. Gu, Z. Yang, D. Basu and P. Mohapatra, "BeamSniff: Enabling Seamless Communication under Mobility and Blockage in 60 GHz Networks," in *2019 IFIP Networking Conference (IFIP Networking)*, Warsaw, Poland, 2019 pp. 1-9.
- (iii) Z. Yang, P. H. Pathak, J. Pan, M. Sha and P. Mohapatra, "Sense and Deploy: Blockage-Aware Deployment of Reliable 60 GHz mmWave WLANs," *2018 IEEE 15th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, 2018, pp. 397-405.
- (iv) Zhicheng Yang, Parth H. Pathak, Yunze Zeng, Xixi Liran, and Prasant Mohapatra. 2017. Vital Sign and Sleep Monitoring Using Millimeter Wave. *ACM Trans. Sen. Netw.* 13, 2, Article 14 (May 2017), 32 pages.
- (v) Z. Yang, P. H. Pathak, Y. Zeng and P. Mohapatra, "Sensor-Assisted Codebook-Based Beamforming for Mobility Management in 60 GHz WLANs," *2015 IEEE 12th International Conference on Mobile Ad Hoc and Sensor Systems*, 2015, pp. 333-341.